Wind Profile and Power Performance Measurements Using a Nine-beam Nacelle Lidar

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Abstract Light detection and ranging (lidar) is a remote sensing method that can measure the average wind speed of larger volumes compared with conventional wind sensors like cup anemometers. Two-beam nacelle lidar is the most representative remote sensor for wind inflow measurement. The remote sensors and conventional wind sensors cannot measure the wind profile as it influences the power generation output. Wind data were measured for a 300-kW wind turbine using both a nacelle anemometer installed in it and a nine-beam nacelle lidar, and then compared. The authors were able to obtain a wind profile by using a nine-beam nacelle lidar, which can irradiate the laser in nine directions and observe the inside of the target volume at a higher resolution than the two-beam version. Unlike nacelle lidars released in the past, the recent nine-beam version allowed also wind profile observations. Since the power output of the turbine was influenced by the wind profile, its relationship with the rotor equivalent wind speed (REWS) was clarified.

Keywords: wind turbine, remote sensing, wind measurement


1. Introduction

Nacelle anemometers (e.g., cup anemometers and wind vanes) are generally used for wind monitoring and machine control during wind turbine operation. However, they are affected by the wakes of the turbine blades, which hinder an accurate measurement of the wind inflow. Therefore, there has been a growing interest in the development of alternative approaches such as light detection and ranging (lidar) methods to overcome this problem. Doppler lidar systems can measure the speed of moving objects: they observe the movement of aerosols, such as minute dust and other particles, in the air using a laser irradiated into the atmosphere to estimate the direction and speed of the wind [1,2]. A nacelle lidar, which measures the wind inflow from a nacelle, enables wind observations not affected by wakes. Wind inflow data are useful to wind turbine operators for grasping accurate information affecting the power generation. Moreover, a machine controller can be activated before the wind reaches the turbine, potentially increasing the power capture by reducing yaw misalignment. A previous research has suggested that nacelle lidars could reduce the cost of energy in some scenarios [3].

Two-beam nacelle lidar is the most representative wind remote sensor. This system uses a laser irradiated in two directions to calculate the wind velocity vector in the target volume. Numerous studies have been conducted on two-beam nacelle lidars, and the wind inflow data obtained using them have been compared with those measured by met masts [4,5,6]. In these studies, both sets of data demonstrated a strong positive linear correlation. However, the two-beam nacelle lidar, which is a simple and inexpensive instrument, cannot measure the wind profile. This parameter is very important in recent wind turbines because, due to the large diameter of their rotors, it influences the power generation output [7,8,9]. The most popular method is to use a tall met-mast. However, it is not realistic to fabricate lots of met masts for wind profile measurements. We were able to obtain a wind profile by using a nine-beam nacelle lidar, which can irradiate the laser in nine directions and observe the inside of the target volume at a higher resolution than the two-beam version. If nacelle lidars can provide wind profiles, they could be an effective and convenient alternative to the met masts. In this research, wind observations at the turbine hub height (z = 0 position) were performed to clarify the typical measurement characteristics of nacelle lidars. Then, we measured the wind profile and defined the relationship between the average wind speed in the rotor swept area and the power generation output.

2. Experimental Setup

2.1. Test Site and Wind Turbine

A field test was performed at Fukushima Renewable Energy Institute, National Institute of Advanced Industrial Science and Technology (FREA, AIST). A mountainous
The area lies at 3 km from the test field and strong winds usually blow from there. Figure 1 shows the 10-min averaged turbulence intensity of the test field measured by the nine-beam nacelle lidar. The bin-averaged value was higher than that of the International Electrotechnical Commission (IEC) category A distribution. Such strong turbulence conditions enabled the evaluation of the impact of turbulence intensity on the lidar system.

Table 1. Design parameters of the wind turbine.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference wind speed</td>
<td>42.5 m/s</td>
</tr>
<tr>
<td>Reference turbulence intensity</td>
<td>0.18</td>
</tr>
<tr>
<td>Cut-in wind speed</td>
<td>3.0 m/s</td>
</tr>
<tr>
<td>Cut-out wind speed</td>
<td>25 m/s</td>
</tr>
<tr>
<td>Survival wind speed</td>
<td>70 m/s</td>
</tr>
<tr>
<td>Sampling rate of nacelle anemometer</td>
<td>1 Hz</td>
</tr>
</tbody>
</table>

Figure 1. Turbulence intensity distribution of the test field measured by the nine-beam nacelle lidar

A Komaihaltec 300-kW upwind wind turbine (KWT300) was located in the test field. This wind turbine is resistant to mountain winds because its turbulence parameter is set above the IEC standard. The reference wind speed and turbulence intensity for its design are listed in Table 1. Since the met mast in the test field was shorter than the hub height of the wind turbine, the wind speeds were measured using the nine-beam nacelle lidar and a nacelle anemometer. The details for the measurement with the nacelle lidar are described later. The sampling rate of the nacelle anemometer (Adolf Thies GmbH & Co. KG) installed in the wind turbine was 1 Hz.

2.2. Nine-Beam Nacelle Lidar

The prototype of the nine-beam nacelle lidar system from Mitsubishi Electric was used. This sensor has a large measurement volume, and the measurable wind speed is limited to the wind speed component in the direction irradiated with the laser (radial wind speed). This nacelle lidar can measure radial wind speeds in nine lines of sight (LOS0–LOS8), as shown in Figure 2. The beams were switched in the following order: LOS3, LOS2, LOS1, LOS5, LOS0, LOS4, LOS8, LOS7, and LOS6. The lidar detected the averaged radial wind speed within the probed length (25 m). Figure 3 shows the measurement locations range; radial wind speed measured in 20 ranges simultaneously. The beams in the lower row hit the ground at \( x/D = -6.7 \). The horizontal and vertical cone angles were \( \theta_1 = 30^\circ \) and \( \theta_2 = 20^\circ \), respectively. The operating specifications of the nacelle are listed in Table 2.

The longitudinal \( (V_x) \) and transversal \( (V_y) \) wind speed components were calculated for the three rows (upper, middle, and lower). The lidar allows two methods for calculating them. Figure 4 (a) shows one of the measurement methods for the wind speed in the middle row, the side-beam measurement. To calculate the wind speed component using the radial speeds \( v_i \) (\( i \) = beam number), wind uniformity in terms of probed volume must be assumed during the measurement period.
Table 2. Measurement parameters of the nine-beam nacelle lidar

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser wavelength</td>
<td>1550 nm</td>
</tr>
<tr>
<td>Number of ranges</td>
<td>20</td>
</tr>
<tr>
<td>Probed length</td>
<td>25 m</td>
</tr>
<tr>
<td>Measurement range(min)</td>
<td>62.5 m</td>
</tr>
<tr>
<td>Measurement range(max)</td>
<td>300 m</td>
</tr>
<tr>
<td>Measurement accuracy of radial wind speed</td>
<td>40 m/s to −20 m/s (plus: headwind)</td>
</tr>
<tr>
<td>Sampling rate of radial wind speed</td>
<td>2.5 Hz</td>
</tr>
<tr>
<td>Sampling rate of horizontal wind speed at middle row</td>
<td>0.25 Hz</td>
</tr>
</tbody>
</table>

The nine-beam lidar can directly measure $V_x$ using the center-beam (Figure 4(b)). If the wind volume uniformity over the measurement time can be assumed, the $V_x$ values measured by the side-beam and by the center-beam should be equal (Eq. (4)). Eq. (4) is not established in principle when the wind vectors in the measurement volume are uniform. Unfortunately, this is an inevitable disadvantage in remote sensing.

$$V_{x,mid} = \frac{V_4 + V_5}{2 \cos \theta_1} = 0.$$  \hspace{1cm} (4)

The wind speed components for the upper and lower rows can be calculated similarly to those of the middle row; $V_x$ for the upper and lower rows was corrected using $\theta_2$. By this way, the vertical wind shear was measured. The radial wind speed was sampled at 2.5 Hz, but it was calculated every time three radial wind speeds were measured. Since the horizontal wind speed was measured from the upper to the lower row, the sampling rate for the middle row was 0.25 Hz.

$$V_{x,up} = \frac{V_1 + V_3}{2 \sin \theta_1 \cos \theta_2}, \quad V_{x,low} = \frac{V_6 + V_8}{2 \cos \theta_1 \cos \theta_2}.$$  \hspace{1cm} (5)

$$V_{y,up} = \frac{V_3 - V_1}{2 \sin \theta_1}, \quad V_{y,low} = \frac{V_8 - V_6}{2 \sin \theta_1}.$$  \hspace{1cm} (6)

Figure 3. Measurement locations range

Figure 4. Outline of the wind speed measurements by the nine-beam nacelle lidar

(a) Side-beam measurement  
(b) Center-beam measurement
3. Results and Discussion

3.1. Data Availability

Sometimes, a measurement beam hits the turbine blades and the wind speed signal is not detected. Therefore, the evaluation of lidar availability is an important topic, because it indicates the percentage of available data samples per unit time. Figure 5 shows the relationship between the 10-min averaged lidar availability of radial wind speed and the turbine rotor speed in the middle row ($x/D = -1.9$). Only the data for the middle row are represented because there was little difference between each row. As the rotor speed increased, the availability of all beams increased continuously. Fast rotor speeds enabled many of the pulses to pass through between the turbine blades. The measurement included a highly unstable case, in which the rotor was stopped in front of the lidar, and in the corresponding plot the availability was zero. The bin-averaged availability almost exceeded 0.8 except for the low-speed cases.

As shown in Eqs. (3) and (4), $V_x$ was measured in two ways. When the side-beam measurement signal could not be obtained, it was supplemented with that measured using the center-beam. Figure 6 shows the availability of $V_{x,mid}$ ($x/D = -1.9$), and the availability did not depend on the rotor speed. Therefore, the probability of obtaining the signal was high, and these results suggest that the center-beam can contribute increasing the $V_x$ data availability and the reliability of the statistical data. Continuous acquisition of wind monitoring data is useful for wind turbine operations.

![Figure 5. Availability for radial wind speeds for the middle row](image)

![Figure 6. Availability of $V_{x,mid}$](image)

3.2. Evaluation of Wind Uniformity

For the wind speed calculation based on two radial wind speeds, the horizontal uniformity of the wind speed and direction in the probed volume was assumed. This section presents an evaluation of the horizontal uniformity of wind speed and direction by using the three beams. Figure 7(a) shows a comparison between the 1-min averaged $V_{x,mid}$ data ($x/D = -1.9$) in the middle row obtained from the side- and center-beam measurements; the difference in wind speed was rather small (<3 m/s). Under strong turbulence conditions, uniformity of wind speed and direction over the measurement period should not be assumed. To analyze the effect of the turbulence intensity, Figure 7(b) shows its relationship with the 1-min averaged wind speed difference; the wind speed difference was approximately 5%–30% greater than that under cut-in wind speed (3 m/s) conditions. For a quarter of all measurement results, the wind speed difference was beyond 10% of the cut-in wind speed. During these measurements, a time delay occurred for each of the three beams. Since it is not possible to measure the wind speed from the three beams simultaneously, the influence of this time delay was not evaluated.
3.3. Comparison of Wind Speed Measurements by Lidar and Nacelle Anemometer

In this study, wind inflow data measured using a nine-beam nacelle lidar were compared with those measured by a reference anemometer. Since the met mast in the test field was shorter than the hub height of the wind turbine, the nacelle anemometer was chosen as reference anemometer. The measurements under wind turbine stop condition have been excluded.

Figure 8 shows a comparison of 10-min averaged wind speeds and wind directions measured by the nacelle anemometer and the nine-beam nacelle lidar at \( x/D = -1.9 \). The measurement volume of the nacelle anemometer and the lidar was apart.; therefore, the influence of the time delay until the wind reaches must be considered. To minimize the influence of the time delay, the measurement location range nearest to the nacelle has been evaluated.

In the middle row, the sampling rate of nacelle anemometer was about 3 times that of the lidar. Since the nine-beam nacelle lidar had less sampling data per 10 minutes, the correlativity of both sensors could have been low, but the data variation was small. The wind speeds measured by the nacelle anemometer were lower than those measured by the nacelle lidar because the rotor-induced wake was also measured. In the high-speed case, where the pitch control of the wind turbine was performed, the relationship between nacelle anemometer and the nacelle lidar was no longer linear. The wind direction difference measured by both sensors was about ± 20 degrees.
3.4. Vertical Wind Profile and Power Performance Measurements

The nine-beam nacelle lidar can measure wind shear and veer. Wind profile measurement is important for multi-megawatt wind turbines with large rotor swept areas. This section shows the wind profiles obtained using the nine-beam nacelle lidar. Figure 9 shows the measurement locations range for the wind profile observation. Since the lidar irradiates the measurement beams in the upstream direction of the wind turbine, the value of \( x \) differed for each \( z \) position.

Figure 10(a) illustrates the profile of \( V_x \). One curve is the wind speed averaged for 10-min. The nine-beam nacelle lidar detected the wind speed decelerated by the ground. In the far measurement range, the shape of the profile collapsed because the measurement signal weakened. Figure 10(b) shows the wind direction difference between each range and that measured at \( z = 0 \) position. A wind direction difference of about 10 degrees was observed in the rotor swept area. The wind direction difference was large in the far range, but the reliability was low because the signal was weak. When \( z \) was negative, the wind direction difference was relatively large due to the influence of the buildings around the wind turbine.

The vertical wind profile of the rotor swept area is important for an accurate power performance measurement. Wagner defined the rotor equivalent wind speed (REWS) using the vertical wind profile in front of the wind turbine [10,11]. The REWS method involves the averaging of the weighted wind speed over the swept rotor area. He measured the wind profile and calculated the REWS using a ground-based lidar and a met mast. In this section, we describe how the REWS was calculated using a similar method in this study. To define the REWS within the rotor swept area, three or more segments are required within the area.

\[
REWS = V_{x,REW} = \left( \frac{\sum_V V_x^3 \frac{A_i}{A}}{3} \right)^{1/3}. \tag{7}
\]

Figure 9. Measurement locations range for wind profile observation. The red circles indicates the range locations

Figure 10. Wind profile and direction measurement results
Figure 11. Wind speed difference

Figure 11 shows the measurement range and the position of the segments. Each segment was located at the middle position of each measurement range ($x/D = -2.3$). $V_x$ was measured using the center- or the side-beam; the $V_x$ value obtained by the directly center-beam measurement was used for the performance calculation. To calculate the REWS, the appearance of the wind speed distribution during the measurement period must be confirmed. Figure 12 shows the relationship between these three wind speeds. The 10-min averaged $V_{x,up}$ and $V_{x,low}$ values were approximately $+6\%$ and $-9\%$ those of $V_{x,mid}$, and the relationship between these wind speeds was highly linear. Since the wind shear measurements depend on the test sites, they were compared with those carried out in other test sites from a previous report[12]. Given the different number of segments and wind conditions of the fields, this comparison was only for reference. The main features of the test sites are shown in Table 3. In the previous research, no nacelle lidar was used for the REWS measurements. Figure 13 compares the wind speed differences of both studies. In this study (site 3: black line), the calculated $V_{x,REWS}$ was often smaller than $V_{x,mid}$. The values obtained for site 3 were close to those of site 1, and the relatively small swept area and flat terrain around the site may have reduced the influence of the wind shear. If also the values for the season of strong turbulence were observed (for example, during the winter season), their difference from those obtained at site 2 could have been clarified. The corrected power curve obtained using the REWS method is shown in Figure 14. The same wind turbine power output was observed for two types of wind speed, and the curve was corrected by a few percent. In the relationship between measured $V_{mid}$ and power, the REWS correction reduced the wind speed in many cases. This caused the power curve of $V_{x,REWS}$ to shift to the left. In the high wind-speed region, as there were few data samples, hardly any difference in the power curve was observed.

4. Conclusion

In this study, wind speeds were measured to understand the measurement characteristics of a nine-beam nacelle lidar installed on a 300-kW wind turbine over a one-month period. The following conclusions were drawn on the basis of our findings.

1. If uniform horizontal wind speed and direction are assumed over the duration of measurement in the probed volume, the $V_x$ values measured by the side- and the center-beam should be equal. The comparison of $V_x$ using two methods is a unique function of the nine-beam nacelle lidar. Since the wind speed differences between the 1-min averaged $V_x$ measured by each beam were $5\%$–$30\%$, the measurement of $V_x$ obtained by the side-beam is an approximate value. Under strong turbulence conditions, the $V_x$ value directly measured by the center-beam has a relatively higher reliability. To detect unreliable data in future researches, it is necessary to decide an appropriate threshold.

2. The nine-beam nacelle lidar was proved effective in the continuous monitoring of wind profile. Since it can measure the wind profile, it is more effective for the power performance evaluation of a wind turbine than a nacelle anemometer, whose measurement area is limited to one point. All three rows of measurements are valid for calculating the REWS.
Table 3. Comparison of the wind shear measurement conditions with those of a previous study.

<table>
<thead>
<tr>
<th>Site no.</th>
<th>Turbine rotor [m]</th>
<th>Hub height [m]</th>
<th>Profile measurement</th>
<th>Site</th>
<th>Number of segments</th>
<th>Number of data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>93</td>
<td>68</td>
<td>Mast</td>
<td>Offshore</td>
<td>9</td>
<td>3580</td>
</tr>
<tr>
<td>2</td>
<td>90</td>
<td>75</td>
<td>Ground-based lidar</td>
<td>Rolling hills, small tree</td>
<td>5</td>
<td>1387</td>
</tr>
<tr>
<td>3</td>
<td>33</td>
<td>41.5</td>
<td>Nacelle lidar</td>
<td>Mountain area 3 km ahead</td>
<td>3</td>
<td>2492</td>
</tr>
</tbody>
</table>

Figure 14. Power curve corrected by the rotor equivalent wind speed (REWS) method

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References


